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Micromechanical Modeling of Laminated Composites With Interfaces and Woven Composites Using the Boundary Element Method

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MICROMECHANICAL MODELING OF LAMINATED COMPOSITES WITH INTERFACES AND WOVEN COMPOSITES USING THE BOUNDARY ELEMENT METHOD

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SUMMARY

The boundary element method is utilized to analyze the effects of fiber/matrix interfaces on the micromechanical behavior of laminated composites as well as the elastic behavior of woven composites. Effective composite properties are computed for laminated SiC/RBSN and SiC/Ti-15-3 composites, as well as a woven SiC/SiC composite. The properties calculated using the computerized tool BEST-CMS match the experimental results well.

INTRODUCTION

In previous work, the boundary element method (BEM) has been utilized to analyze the elastic, heat conduction and thermal expansion behavior of laminated composite materials with perfect bonding at the micromechanical (constituent) scale (ref. 1). In many actual materials, the fiber/matrix interface is more complex and must be accounted for. One approach that was used previously involved utilizing the rule of mixtures and laminate theory, varying the fiber modulus based on the bonding condition (ref. 2). Another analytical approach used previously considered the interface to be a distinct composite constituent, and the micromechanical equations used to compute effective composite properties were revised accordingly (ref. 3). Discrete methods used previously included modeling the interface using gap elements in a finite element analysis (ref. 4), as well as explicitly modeling the interface using finite elements (ref. 5).

Woven composites have been investigated as a means to improve the interlaminar properties of composites and to obtain the multidirectional properties of composite laminates with less of the difficulties associated with ply layup (ref. 6). Analytical methods used previously to analyze woven composites include methods such as the mosaic model and the fiber undulation model (refs. 7 and 8), in which laminate theory was utilized. Researchers such as Whitcomb and Sankar (refs. 6 and 9) have used finite element methods to analyze woven composite behavior.

The objectives of this paper are to demonstrate the use of the boundary element method in analyzing fiber/matrix interface behavior for laminated composites, and the elastic behavior of woven composites, on the micromechanical scale.

ANALYSIS METHODOLOGY

The computerized tool BEST-CMS (Boundary Element Solution Technology-Composite Modeling System) (ref. 10) is utilized to conduct the boundary element analyses in this study. To model a composite material using BEST-CMS, the outer surface of the composite matrix can be discretized with quadrilateral or triangular surface elements. Eight noded quadrilateral elements are used for this study.

To model the fibers of the composite, specially formulated "Insert Elements" are used. With these insert elements, only the centerline of the fiber, with its corresponding fiber radius, is defined. Fiber surfaces and the variation of the field variables in the plane of a fiber cross-section are represented analytically, and internal to the computational procedures within BEST-CMS. The variation of the field variables along the fiber length is calculated by using numerical integration. In BEST-CMS, both straight and curvilinear fibers are allowed.

BEST-CMS includes provisions to model spring and frictional fiber/matrix interfaces. The interface behavior (including perfect bonding, sliding interfaces, and progressive debonding with gap openings and frictional slipping) is incorporated directly into the boundary integral formulation, obviating the need for cumbersome discretization requirements. The linear interface is modeled by defining spring constants normal to the fiber and in the fiber longitudinal direction.

To model the nonlinear spring-Coulomb interfaces, spring constants normal and longitudinal to the fiber are defined, along with a friction coefficient (the coefficient of friction between the fiber and the matrix). In the direction normal to the fibers, linear spring resistance is modeled when the tractions are compressive. When the tractions become positive, the tractions are set to zero and an interfacial gap forms. In the longitudinal direction, linear spring resistance is used until the principal longitudinal tractions reach a slip limit defined by the friction coefficient through the Coulomb friction criterion. Once the limit is reached, the interface is defined to have reached a maximum level of traction, and only displacement changes can occur (ref. 10).

There are several important limitations to BEST-CMS which should be noted. Fiber ends as free surfaces cannot be represented due to the insert element formulation, which results in the fibers lying entirely within the matrix outer surface. Since the fibers cannot intersect the outer surface of the model, applied surface loads are applied to the matrix outer surface, and must be transferred through the matrix to the fiber. The composite fibers also must have a circular cross-section along the entire length, which can affect the modeling of angleplied laminates and woven composites. Another assumption in the boundary element formulation is that the Poisson's ratio of the fiber is set equal to the Poisson's ratio of the matrix. This assumption has been shown (ref. 10) to be valid for most composites. Finally, rigid plane boundary conditions are not specifically available within BEST-CMS, which can affect the calculation of effective composite properties. Another effect of this limitation is that nodal tying, periodic boundary conditions and other multi-point constraints required for more realistic boundary conditions cannot be applied to the boundary element models, which can particularly affect the results for angleplied composites. To minimize the effects of this limitation, results are taken as far from the point of boundary condition application as possible. Additionally, in the calculation of effective properties, equivalent (average) strains are computed over the model region of interest.

ANALYSIS OF SiC/RBSN WITH LINEAR INTERFACES

The first set of analyses involve computing the effective composite elastic properties for a SiC/RBSN composite system. The composite consists of silicon carbide (SCS-6) fibers, with a fiber diameter of 142 μm, embedded within a reaction bonded silicon nitride matrix. A fiber volume fraction of 0.30 is used. For the analysis, the fiber modulus is assumed to be 390 GPa, the matrix modulus is 110 GPa, and the matrix Poisson's ratio is 0.22 (ref. 2). An important point to note is that only the initial linear portion of the material behavior is considered, before any matrix cracking or material nonlinearities appear.

As a first approximation, the fiber/matrix interface is modeled as a linear spring interface. The spring constant normal to the fiber is set to a low value (near zero), while the spring constant in the fiber longitudinal direction is set to a very high value (near infinity). These choices are made in order to simulate the observations made by Bhatt (ref. 2) that the SiC/RBSN interface appears to have a high level of load transfer between the fiber and matrix in the fiber longitudinal direction, but a low level of load transfer (due to debonding) normal to the fibers.

The boundary element model utilized for these analyses is a four cell square model, where the model thickness equals the width. Figure 1 shows a sample boundary element model for a [0] composite. This model is based on the COMGEN-BEM (ref. 11) four cell rectangular model. The results were shown to be independent of model depth. Roller nodal constraints are applied to the back (y-z), left (x-z) and bottom (x-y) faces of the model, and a uniform pressure load is applied to the front (y-z) face. The equivalent (average) strain on the front face is used to calculate the composite modulus, while the front and right face equivalent strains are used to calculate the Poisson's ratio. Residual stresses resulting from material processing are not accounted for in the analysis.

Figure 2 shows the variation of the longitudinal tensile modulus as a function of the fiber orientation angle. Fiber orientations of $[0]_8$, $[10]_8$, $[45]_8$ and $[90]_8$ are examined. For each orientation, experimental results (ref. 2) are compared to calculated values using a perfect bond interface and the spring interface discussed above. For the [45] laminate, a "loose" interface is also used in which both normal and longitudinal spring constants are set to very low values. The reasons for examining this additional interface condition will be discussed below.

As can be seen in figure 2, the modulus results obtained by using the spring interface match the experimental results fairly well, except for the [45] orientation. Specifically, the [0] laminate has a 11.6 percent error, the [10] has a 6.6 percent error, the [45] has a 41.4 percent error, and the [90] has a 9.6 percent error. Applying the "loose" interface to the [45] laminate reduces the error to 6.0 percent. This result indicates that for the [45] laminate there is little load transfer between the fiber and matrix both normal to the fibers and in the fiber longitudinal direction. The "loose" interface results are only shown for the [45] laminate since the results are only meaningful or significant for this laminate orientation. One reason for the modestly large numerical discrepancy for the [0] laminate is most likely due to the BEST-CMS assumption that fiber ends as free surfaces cannot be represented. This effect has been noted and discussed in a previous report (ref. 1). Scatter in the experimental results may also affect the comparison to the calculated values. Overall, the results indicate that the fiber/matrix interface plays a strong role in the material behavior. The results calculated by using a perfect bond interface, particularly for higher fiber angle orientations, are much less accurate, and show much less dependence on fiber orientation angle than is seen in the results computed by using the spring interfaces.

To examine the interface effects on cross-ply and angleply laminates, the longitudinal modulus and Poisson's ratio are computed for $[0_2/90_2]_s$ and $[+45_2/-45_2]_s$ laminates. These results are plotted in figures 3 and 4, along with results from [0] and [90] laminates for comparison. Once again, experimental results are compared to results calculated using a perfect bond, the spring interface defined earlier, and, for the [±45] laminate, the "loose" interface defined earlier.

The results in figure 3 show that the interface plays a significant role in the composite behavior. Using the spring interface, the [0/90] laminate has a 23.8 percent error as compared with the experimental and the [±45] laminate has a 46.4 percent error. Using the "loose" interface for the [±45] laminate reduces the modulus error to 10.3 percent, indicating that this laminate exhibits little fiber/matrix load transfer both normal to the fibers and in the fiber longitudinal direction. There are several possible causes for the moderately large error seen in the [0/90] laminate. First, the BEST-CMS assumption that fiber ends as free surfaces cannot be represented probably affects the results in the 0° ply. Second, there is a large gradient in the displacements between the 0° ply and the 90° ply due to the fact that a rigid plane multi-point constraint cannot be defined. The displacement gradient might also affect the results. Scatter in the experimental results may also affect the comparisons to the calculated values. Overall, the results obtained by using a spring or "loose" interface are more accurate, and showed more dependence on laminate orientation, than the results calculated by using a perfect bond. These results again indicate that the fiber/matrix interface plays a strong role in the composite behavior.

The Poisson's ratio results for the four laminates examined are shown in figure 4. Using the spring interface, the [0] laminate has a 15.7 percent error as compared to the experimental, the [0/90] laminate has a 2.5 percent error, the [±45] laminate has a 59.7 percent error and the [90] laminate has a 13.1 percent error. Using the "loose" interface for the [±45] laminate reduces the error slightly to 39.44 percent. There is no clear reason for the large discrepancy in the [±45] laminate, but it could possibly be related to the fact that the experimental specimens for this layup exhibited much greater matrix plasticity (not accounted for in the analysis) than was seen in the other layups (ref. 2). Overall, however, the results obtained by using the various interface conditions yield more accurate results than those obtained by using a perfect bond.

ANALYSIS OF SiC/Ti-15-3 WITH NONLINEAR INTERFACES

The next set of analyses involve examining a SiC/Ti-15-3 composite. The material consists of SCS–6 fibers embedded in a titanium alloy (Ti-15V-3Cr-3Al-3Sn) matrix. A ply orientation of $[90]_8$ is examined, and a fiber volume fraction of 0.34 is used. For the analysis, the fiber modulus is assumed to be 390 GPa, the matrix modulus is 88 GPa, the matrix Poisson's ratio is 0.32, and the friction coefficient of the fiber/matrix interface has been determined experimentally to be 0.02 (ref. 12). The composite stress-strain curve exhibits an initial linear region with full fiber/matrix bonding, followed by a second linear region of a lower slope. The second linear region is a result of fiber/matrix debonding (ref. 12). The two linear regions are then followed by a nonlinear region (ref. 12).

To model the fiber/matrix interface for this material, a perfect bond is used to obtain the initial modulus of the material, while the nonlinear spring/Coulomb interface is used to obtain the secondary modulus. For the nonlinear interface, very large (near infinity) spring constants are used with a friction coefficient of 0.02. Ideally, to model the complete behavior range of this material, the nonlinear interface would be utilized for an entire analysis. The ideal complete analysis would first include a thermal cool-down in order to impose compressive residual stresses, followed by an incremental loading. In this manner, the actual point of debonding, along with both the initial and secondary modulus, could be determined. Unfortunately, the current version of BEST-CMS cannot incorporate multiple load steps into an analysis with nonlinear interfaces, which prevented us from carrying out a complete analysis. In the analyses that are carried out, residual stresses are not incorporated since they have been shown to primarily control the point of debonding (refs. 1 and 4). For these analyses, only the initial and secondary moduli are computed.

For the boundary element analyses, a one cell square model (similar to the four cell square model used above) is used. Roller nodal constraints are applied to the back (y-z), left (x-z) and bottom (x-y) faces. A uniform pressure load is applied to the front (y-z) face, perpendicular to the fiber direction. The equivalent strain results are then measured on the front face.

The stress-strain results for the two interface types are plotted in figure 5 along with the experimental curve, obtained from reference 12. The analytical models are loaded to an arbitrary stress level, which accounts for the sudden end to the plots of the computed results seen in the figure. As can be seen from the figure, the slope of the calculated curve with a perfect bond closely matches the slope of the initial linear portion of the experimental stress-strain curve. The results obtained by using the nonlinear fiber/matrix interface yield a slope that is fairly close to the slope of the second linear portion of the experimental curve, indicating that the interface has debonded due to the tension loads normal to the interface. Discrepancies between the experimental and computed results in the second linear region may be due to the onset of matrix plasticity in the experimental specimens, which is not accounted for in the analysis. The results indicate that BEST-CMS can accurately model the complete range of fiber/matrix bonding conditions. As indicated earlier, future work will entail conducting a complete analysis of the material, with nonlinear interfaces and residual stresses, in order to capture the complete range of material behavior.

ELASTIC ANALYSIS OF WOVEN COMPOSITES

The final analysis involves examining the material behavior of a SiC/SiC plain weave composite. To model the woven composite, the COMGEN-BEM four cell square rectangular model is modified (fig. 6). Curvilinear insert elements are used to model the fiber tows. Two inserts are used to represent each full fiber tow since BEST-CMS only allows circular fiber cross-sections, and the actual fiber tows have an elliptical shape. The four insert by four insert model is used in order to allow the fiber crimping to be taken into account. Utilizing the boundary element method to model woven composites offers a distinct advantage over finite element methods, in that it would be extremely difficult to construct a full finite element model of this type of material. Also, by explicitly modeling the fiber tows the detailed local behavior in fiber and matrix dominated regions can be examined.

In woven ceramic matrix composites, the material porosity is significant and must be accounted for. In the boundary element models, the fiber volume fraction (and thus the fibers) is explicitly defined, with the remainder of the model consisting of matrix and pores. For these models, the fiber modulus is explicitly input into BEST-CMS, while for the "matrix" (actually consisting of matrix and pores) an equivalent modulus is input. As a first approximation, the given matrix modulus and a pore modulus of zero is used in a rule of mixtures calculation in order to compute the effective "matrix" modulus. Of course, this simple approximation will only work in the linear range of the material behavior.

For this analysis, a plain weave [0/90] composite consisting of Nicalon fiber tows in a silicon carbide matrix is used. A fiber volume fraction of 0.40 is used, with a fiber modulus of 200 GPa. The matrix modulus is 350 GPa, the matrix Poisson's ratio is 0.2, and a matrix volume fraction of 0.4 is used (ref. 13). Only the initial linear portion of the material behavior is modeled, and a perfect bond between the fiber and matrix is assumed.

The boundary conditions applied to the model are similar to the ones used previously. Roller nodal constraints are applied to the back (y-z), left (x-z) and bottom (x-y) faces of the model, and a uniform pressure load is applied to the front (y-z) face of the model. The equivalent strain on the front face is computed to obtain the modulus.

The initial modulus for the material is computed to be 225.96 GPa, which is 5.1 percent off from the experimental value of 215 GPa (ref. 13). Increasing the matrix volume fraction to 0.531 yields a calculated modulus of 283.58 GPa, which is 4.75 percent off from the experimental value of 270.73 GPa (R.J. Carter, 1992, E.I. DuPont De Nemours & Co. (Inc.), Newark, DE, personal communication). The close match between the experimental and calculated results indicates that the boundary element method shows promise in modeling woven composites.

CONCLUSIONS

The ability to incorporate interface effects into boundary element analyses of composite materials on the micromechanical level has been demonstrated. The results computed for SiC/RBSN and SiC/Ti- 15-3 composites match the experimental results fairly well when interface conditions are used. BEST-CMS has also been shown to have the ability to analyze composites with complex architectures such as woven composites. Overall, the boundary element method continues to show promise in providing an alternative approach to analyzing the micromechanical behavior of composite materials.

Several areas of future work will be undertaken. Analyses with an elastic-plastic matrix material will be undertaken, as well as analyses combining nonlinear interfaces with residual stresses. The woven composites models will be refined, and more complex behavior of woven composites such as oxidation will be examined. In addition, the BEST-CMS code will be modified in order to improve the nonlinear material modeling, add the capability to model composite damage, and improve the modeling of woven composites.

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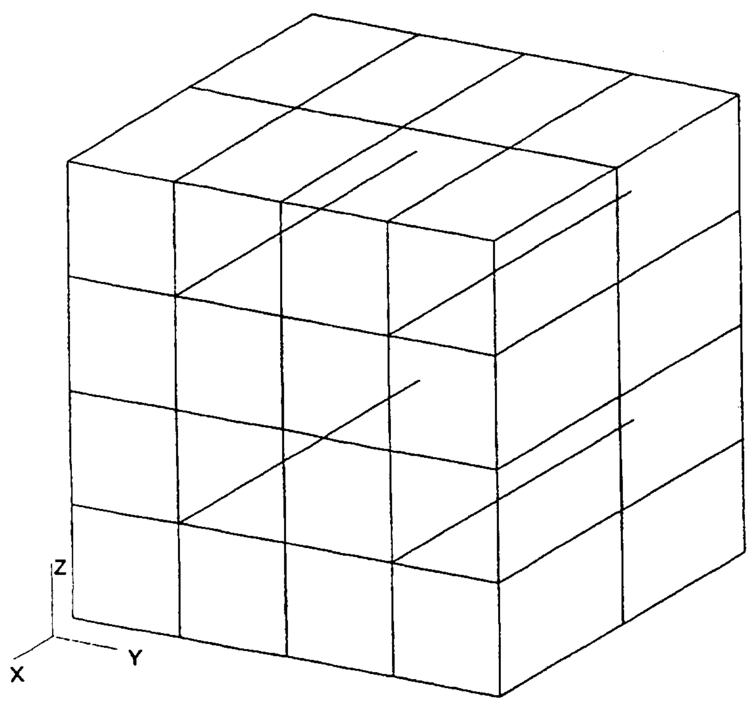

Figure 1.—Boundary element four cell square model for [0] laminated composite.

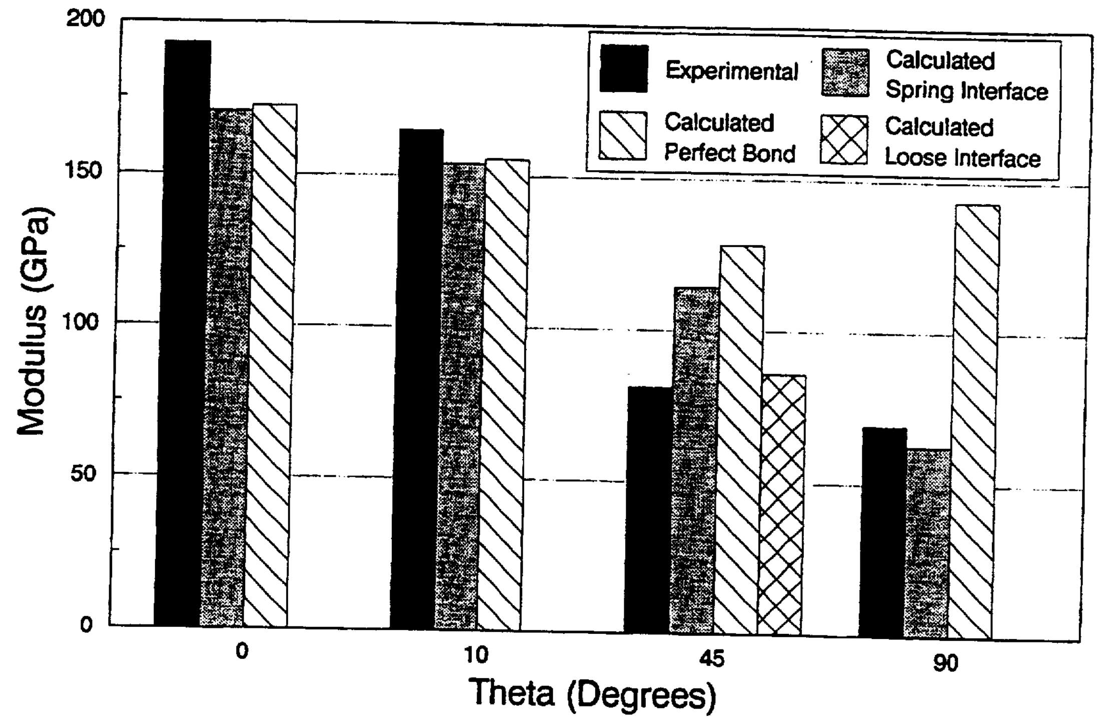

Figure 2.—Effect of fiber orientation angle on modulus for SiC/RBSN.

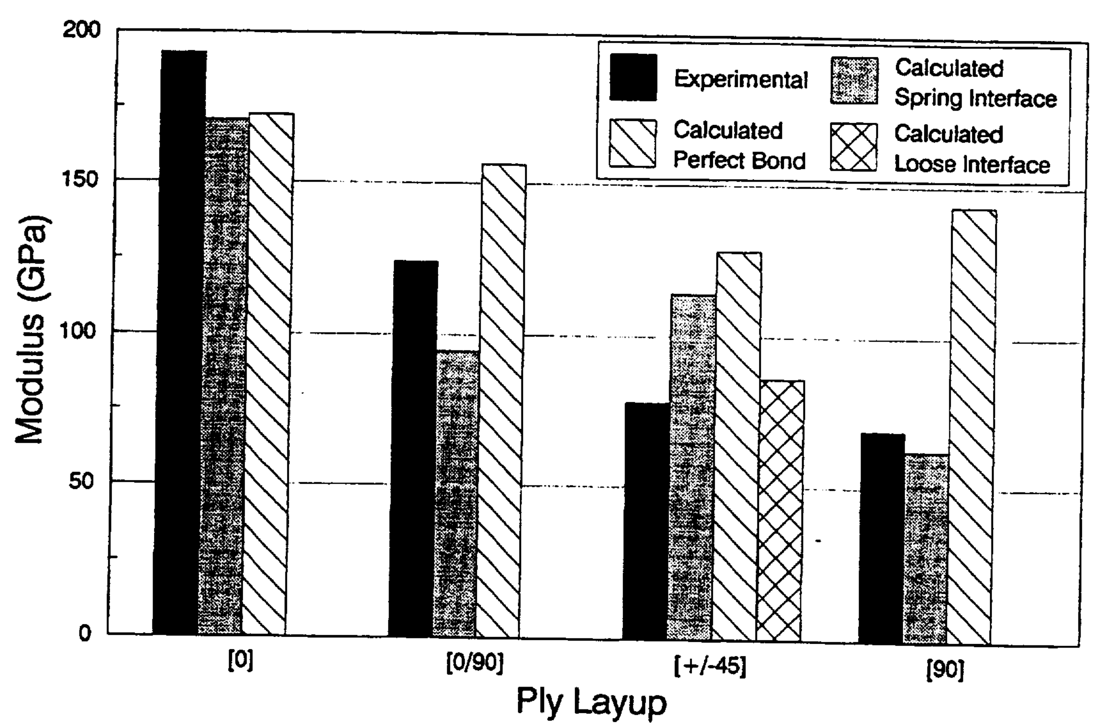

Figure 3.—Effects of ply layup on longitudinal modulus for SiC/RBSN.

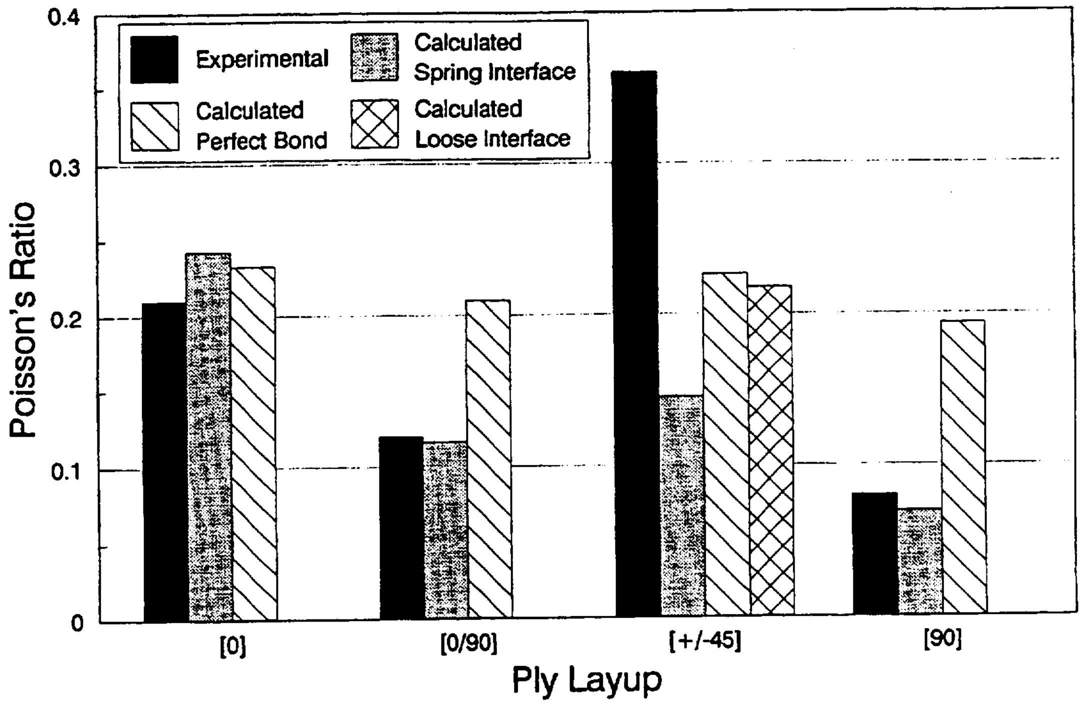

Figure 4.—Effects of ply layup on longitudinal Poisson's ratio for SiC/RBSN.

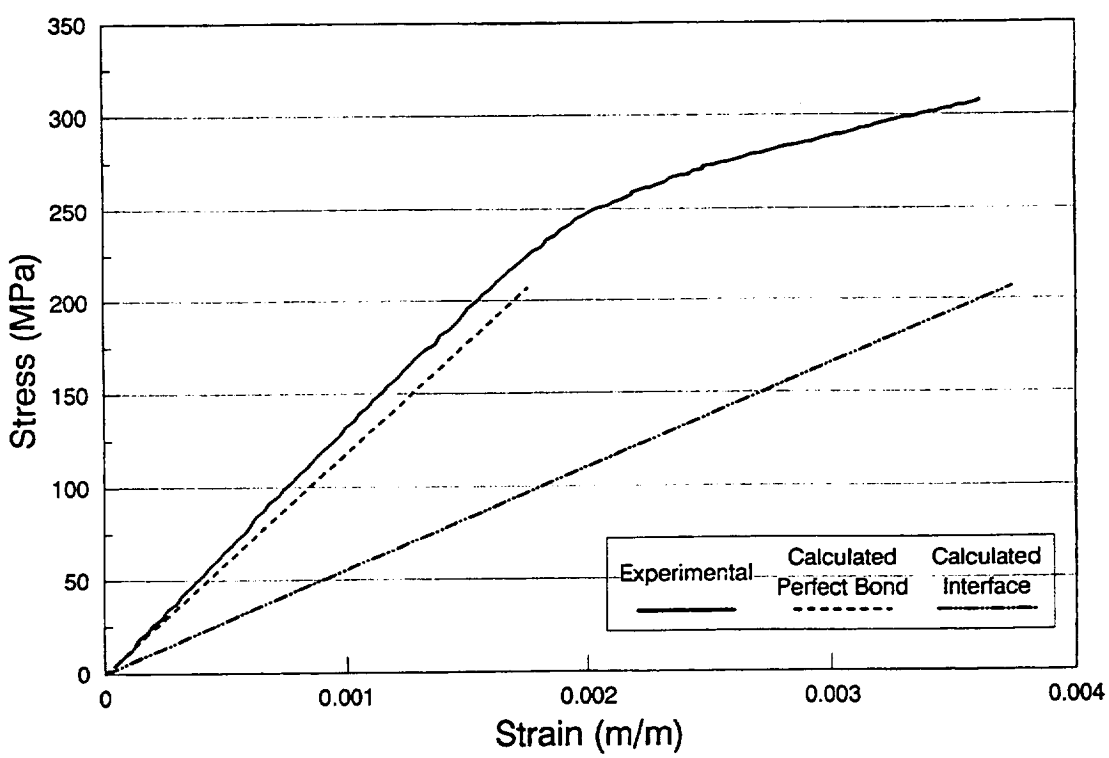

Figure 5.—Effect of interface on modulus for SiC/Ti-15-3.

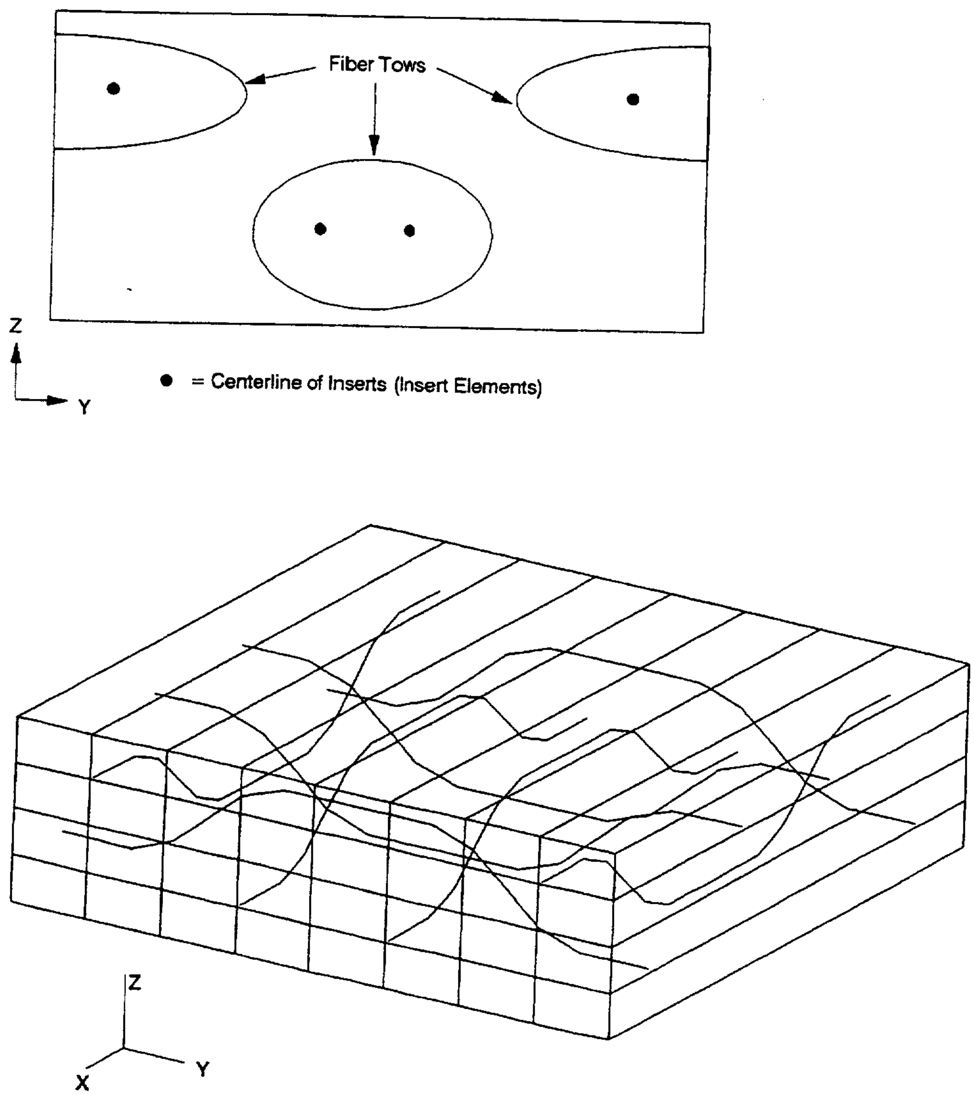

Figure 6.— Boundary element model for woven composites.

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13. ABSTRACT ***(Maximum 200 words)***

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